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XI.

CONTRIBUTIONS FROM THE PHYSICAL LABORATORY OF HARVARD UNIVERSITY.

ON THE HEAT PRODUCED IN IRON AND STEEL BY REVERSALS OF MAGNETIZATION.

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THE object of our investigation was to determine whether the heat which is generally attributed to rapid magnetizing and demagnetizing is really due to this cause, or to induction currents in the mass of the iron. Our work, however, had in the beginning a more practical object. Since cylinders of iron and steel are heated when they are made the cores of electro-magnets, and are submitted to the effects of rapidly alternating currents, it was thought that they might exhibit different degrees of heating, and therefore that a process of determining the character of iron and steel might be based upon the phenomena observed, which could be called an electro-magnetic criterion of certain physical properties of these metals. It is well known that chemical analyses of steel and iron throw very little light upon their physical properties, such as tenacity and elasticity in general. There is no satisfactory test for the properties of different steels save by a testing-machine, and this is not readily applicable in many cases. If a method could be devised which depended simply upon electrical and magnetic phenomena, it would be a valuable aid to the metallurgist.

The amount of sulphur, of phosphorus, and other ingredients besides iron, is very small in steel, and it could hardly be expected that their presence or absence could be detected by the difference of heat developed under the influence of alternating currents, unless this heating is really due to molecular agitation produced by magnetization and demagnetization. If the heating is due to alternating induction currents in the mass of metal, there should be very little difference in the amount of heat developed by different specimens of steel; for their electrical resistance would not differ sensibly from the presence or absence of a fraction of one per cent of phosphorus or sulphur. If the heating is due to magnetization or demagnetization, and to an

actual twisting of small magnets in their beds, then the molecular arrangements consequent upon different admixtures of various ingredients might produce more heat in one specimen than in another, and thus afford a criterion of the character of the steel.

We therefore determined to try our experiments on a practical scale, — to employ a powerful alternating dynamo-electric machine, and to submit the specimens of iron and steel, in a very strong magnetic field, to the alternating currents, in order to develop a large amount of heat in a short time. The dynamo-machine was of the Wilde type, and made six thousand reversals of current per minute. The currents were passed through a dynamometer, — which is described in the Proceedings of the American Academy of Arts and Sciences, 1878–79, p. 122, — and also through the coils in which the specimens were placed. A simple arrangement of keys enabled us to throw the coil, enclosing the specimen, into the circuit, and to withdraw it, — the current passsing continuously through the dynamometer. The latter instrument gave deflections which were proportional to the strength of the currents employed, and to the amount of work done in heating the iron specimens, although the absolute strength of the currents could not be determined without a calculation of the self-induction of the coils and of the dynamo-machine. The specimens of iron were immersed in a cylindrical copper calorimeter filled with mercury, and the space between the walls of the calorimeter and the surrounding coil was packed with infusorial earth, which is a very good non-conductor of heat. The duration of each experiment was one minute. In this time the strength of the current was observed, and the rise of the thermometer was ascertained. During the space of one minute the coil employed did not heat perceptibly. In two minutes, however, the coil was heated, and it was therefore determined to limit the time of the experiments to one minute, and to take the rise of temperature during that period. The amount of mercury and the pieces of iron were carefully weighed, with a view of using the data quantitatively; but the subsequent experiments showed that this was impossible, for the heating effort was confined to the outer layer of the iron, and the temperature at the centre of the bar was very much less than that at the exterior.

In the following table the first column contains the number of the iron, and opposite the number is the analysis. The third column contains the weights of metallic cylinders employed. The fourth column gives the current when one coil — called green for convenience — was used; the fifth column gives the temperature for this coil; the sixth, the current for another coil, — red coil; and the seventh, the temperature for the latter coil.

No.	Manganese.*	Weight.	Current.	Temperature.	Current.	Temperature.
			Green.	C.°	Red.	
14	0.493	1398.12	9.05	17.27	11.10	17.00
32	0.584	1359.65	9.15	16.60	10.45	17.10
11	0.282	1363.00	9.15	17.66	10.00	13.05
83	0.014	1363.10	8.31	15.00	10.46	16.00
113	0.015	1358.10	8.46	15.00	10.46	16.30
231	0.020	1364.55	9.46	13.30	10.20	13.94
115	0.031	1362.57	8.10	15.00	10.49	15.10
107	0.032	1391.90	8.15	16.00	10.37	15.70
	Total Carbon.†					
83	1.044	1363.10	8.31	15.00	10.46	16 00
119	1.142	1366.70	7.46	14.80	9.43	13.80
120	1.318	1370.63	8.14	13.00	9.46	13.77
112	0.873	1363.00	8.53	17.20	11.10	17.00
113	0.923	1358.10	8.46	15.00	10.40	16.30
115	0.946	1362.57	8.10	15.00	10.49	15.10
104	0.294	1391.65	9.05	16.55	10.55	16.27
106	0.301	1394.17	8.55	16.55	10.37	13.55
231	0.009	1364.55	9.46	13.30	10.20	13.94
230	0.463	1435.12	8.33	14.40	8.33	12.10
121	0.257	1346.52	7.50	14.70	9.28	14.00
	Combined Carbon.‡					
11	1.142	1363.00	9.15	17.66	10.00	13.05
12	1.244	1363.55	9.16	17.66	11.07	16 27
83	1.024	1363.10	8.31	15.00	10.46	16.00
118	1.079	1358.62	7.50	15.33	8.56	
119	1.112	1366.70	7.46	14.80	9.43	13.80
120	1.285	1370.63	8.14	13.00	9.46	13.77
6	0.846	1370.80	9.23	17.83	10.05	13.94
38	0.012	1349.00	8.50	16.40	10.15	17.16
37	0.042	1349.90	8.55	17.90	10.30	16.20
45	0.116	1336.18	10.55	17.60	11.25	17.70
33	0.135	1399.00	9.00	17.05	11.07	16.70
122	0.383	1394.80	7.40	15.30	9.18	14.30
	Phosphorus.§					
36	0.315	1349 00	8.50	16.40	10.15	17.16
32	0.138	1359.65	9.15	16.60	10.45	17.10
33	0.113	1399.00	9.00	17.05	10.15	17.16
37	0.109	1349.90	8.55	17.90	10.30	16.20
50	0.104					
6	0.019	1370.80	9.25	17.40	10.05	13.94
1	0.014	1355.67	7.40	13.00	10.03	13.83
121	0.014	1346.52	7.50	14.70	9.28	14.00
83	0.013	1363.10	8.31	15.00	10.46	16.00

These results show that this method affords no criterion of the physical properties of iron and steel. The molecular structure of the various specimens employed was not sufficiently modified to enable

* Different proportions of manganeses give no result.

† Total carbon, — no difference.

‡ Apparently, the less carbon, the greater heat.

§ No conclusion. If any effect, phosphorus does not determine it.

us to determine any differences in molecular heating, — if the heat developed by magnetizing and demagnetizing is due to molecular heating. If it is due entirely to induction currents in the metals, the slight changes in electrical resistance produced by small quantities of sulphur, of phosphorus, and of carbon would be inappreciable in the masses of iron which we used, and we should expect to obtain under the same conditions the same rise in temperature for the different specimens of steel. Our previous work* on cobalt and nickel must therefore have been affected by some error.

We next determined to ascertain if the heating was confined to the surface of the metallic cores. Theory indicates this to be the case, whether we adopt the hypothesis that the heat is due to magnetization and demagnetization, or the hypothesis that it is produced by induction currents. We could not find, however, any experiments upon this point. The bars were prepared as follows. Each one was bored one half its length. At the outer end of the hole a shoulder was turned in order that a short piece of glass tubing could be cemented in. One thermometer was placed in the mercury surrounding the bar of iron, and another was hung in the hole in the centre of the bar, the hole being also filled with mercury. It was difficult to distinguish between the conduction of heat and the evolution of heat. The rise of temperature indicated by the inner thermometer, however, was probably entirely due to conduction of heat, as can be seen by comparing the amounts of mercury surrounding the two thermometers.

The following table exhibits the results obtained. In the third column an arbitrary designation is given to the electro-magnetic coils which were used in the experiments.

No. of Exp.	No. of Iron.	Kind of Coil.	Weight of Mercury on outside of Iron.	Weight of Mercury in cavity of Bar.	Thermometer in outer Mercury.		Thermometer in Mercury in cavity.	
					Before passage of Current.	After passage of Current.	Before passage of Current.	After passage of Current.
			Grammes.	Grammes.				
11	1	Red.	3317.9	39.07	10.7	23.0	10.5	21.5
12	12	"	"	"	13.0	26.5	12.5	24.0
13	36	Green.	"	"	13.1	27.3	13.0	25.0
14	32	"	"	"	16.0	31.0	15.5	28.0
15	113	"	"	"	16.0	31.0	15.5	28.0
16	108	"	"	"	16.8	32.0	16.2	30.0
17	1	"	"	"	21.0	34.5	20.5	32.0
18	12	"	"	"	21.5	36.0	21.0	32.5

Weights in Grammes.					
	36	1320.7	108	1336.0	The weights differ from the previous ones of same bars, as some metal has been bored out of the centres.
	32	1332.0	1	1323.4	
	113	1328.6	12	1335.0	

* Proceedings of the American Academy, 1878–79, p. 114.

If the heating is due to molecular movements produced by magnetizing and demagnetizing, — and the musical note is adduced as an evidence of this, — the bar would vibrate as a whole, and would become heated throughout on account of this vibration. It is difficult to conceive how the surface action of magnetism can communicate vibrations to a solid bar of iron one inch and a half in diameter. If the bar vibrates as a whole, a certain amount of heating of the bar takes place throughout its interior. The heat in the interior of the bar, however, must be less than that at the exterior, where the magnetization exists in full strength. We believe, however, that the musical note is due to a forced vibration in the coil of the electro-magnet, — possibly due to electro-magnetic attractions; for the note can be heard when the iron core is removed, and is stronger when the core is in place simply because the magnetic field is strengthened.

The appearance presented by iron filings strewn upon the pole of a straight electro-magnet, which is submitted to the action of an alternating current, shows very strikingly the fact that it takes time to magnetize, and that magnetism resides upon the exterior of electro-magnets. Under the influence of strong currents alternating six thousand times a minute, the electro-magnet is still capable of attracting an armature with great force. The filings arrange themselves as a narrow fringe or ring upon the circumference of the end of the cylindrical bar constituting the core of the electro-magnet, leaving the surface of the end of the cylinder entirely free from filings. If filings are scattered upon this free portion of the surface, they waltz to the circumference. The fringe of iron filings vibrates in unison with the alternating currents.

In connection with this investigation, it may be interesting to refer to some experiments made by Lt.-Comm. A. G. Caldwell, U. S. N., and ourselves, on demagnetization. These experiments were made in 1880, but have not been published.

Perfect demagnetization, or entire absence of magnetism in a mass capable of magnetism, is a condition of great rarity. Approximate demagnetization has been brought about with some difficulty, but delicate tests would show traces of polarity.

We have, however, discovered a method by which complete demagnetization may be rapidly and easily produced. The principle involved is the setting up of a state of powerful magnetic vibration, by which all previous magnetic conditions are obliterated, and on the subsidence of which no polarity remains. This state of vibration is induced by an alternating current of *sufficient strength*. By this an

effect is induced in the magnetized mass which can only be compared to a vibration or wave. The reversals of the inducing current cause corresponding reversals of polarity in the body acted on, and as these reversals are continuous and very rapid (5,000 to 6,000 per minute, for example), a molecular vibration probably arises. It is probable that a condition of strain or set is one of the phenomena of magnetism.

The particles have been made to assume a certain definite or polar relation or position. When, however, a powerful movement or vibration is caused, it is evident that when this vibration has become complete, — that is, involving the whole mass, — all previous conditions of strain or "permanent set" will be overcome. It must be remarked that, in order to perfectly attain this result in all cases, the exciting force must be sufficient.

When the alternating current ceases, the body acted on is left perfectly free from polarity. It is, however, in a state of extreme sensitiveness, and must be allowed to remain at rest for a short time. If it is placed north and south, it will assume polarity, and very strongly, if struck with a hammer when held in the position of the dip.

Demagnetization requires but a short time in most cases, — from one to three minutes if the current is properly adjusted. There are several ways of performing the experiment, but it will be sufficient at this time to refer to a few of them. The most effective method is to enclose the mass to be demagnetized in a coil of such a length that the whole body will occupy an approximately central position. The coil may be a simple one, in which case it must stand east and west, and before removing the object the electric machine must be stopped, and the current allowed to die away. Also, when the object is taken out of the coil, it must be carefully shielded from the earth's induction. Or the coil may be so constructed that it can be opened or divided at the centre without breaking circuit, and then the object can be taken out without stopping the alternating current. One of the coils we used was made of No. 12 copper wire, wound as one coil, but in halves, with an elastic connection. It is well known that, with an alternating current, self-induction in the coil materially reduces the current, and therefore the coil should be one of a comparatively small number of turns.

Demagnetization of small masses, not too retentive of magnetism, may be performed by placing them on the end of a bar contained in the coil, which is a part of the alternating circuit. A bar of low steel, somewhat longer than the coil, was used, and the small objects placed on its projecting end.

Perfect demagnetization is attained with varying difficulty. Ordinarily, it is rapidly and easily accomplished. Sometimes a longer time is required, or a more intense action. In numerous experiments, we derived the alternating current from a Wilde machine which gave about 6,000 reversals per minute. This rate is probably greater than is required or desirable, except in extreme cases. About 3,000 to 4,000 reversals would be a better general rate, although of course the operator should arrange his apparatus so that he could get more reversals if necessary. Failure will result if the speed is too great, as might be expected if the view here taken is correct. Usually, it will be more convenient to employ, instead of an alternating machine, a battery with a reverser arranged for varying speeds.

One application of this method is to the demagnetization of watches. Watches strongly magnetized are completely demagnetized by one to three minutes' exposure in the coil. Frequently unsuspected traces of magnetism cause annoying irregularity of action of a watch. This method enables us entirely to remove this difficulty.

Some very curious and interesting results were obtained by experimenting with magnetite.

A specimen of very pure magnetite, from North Carolina, showing marked magnetic properties, was completely demagnetized by a somewhat long exposure to the action of an alternating current applied as described above. Before demagnetization the piece had shown consequent points, although in general it possessed polarity. After treatment it attracted either end of a very light suspended needle indifferently, and when any part of the mineral was presented, just as a piece of soft iron would do. The demagnetized specimen was then placed across the poles of an electro-magnet excited by a strong current from a Gramme machine. It became strongly magnetic, with distinct poles, and without the consequent points it at first had. After this it was treated like an ordinary bar magnet, and magnetized or demagnetized at will.

Another more impure piece was originally less strongly magnetic, and was demagnetized with great difficulty. At first it displayed no general polarity, having consequent points irregularly distributed. After demagnetization it received induced magnetism and became polar, but it was a much feebler magnet than the previous specimen. Demagnetization was afterward performed more easily than at first.

A still more impure specimen was treated, but with the means at hand it was not *perfectly* demagnetized, although so nearly was this done that only traces of magnetism were noticeable.

The results of our work can be stated as follows: —

1. The heat developed by reversals of magnetization is probably due to induction currents, and not to molecular vibrations; for considerable changes in the molecular structure of different specimens of iron and steel fail to show differences in the amount of heat developed.

2. The heating of iron cores of electro-magnets, which are submitted to alternating currents, is confined to the surface until conduction equalizes the heat of the cores.

3. The musical note emitted by the core is the note of the coil, due to the number of reversals of the machine, and is merely strengthened by the metallic core of the electro-magnet. This note should not, therefore, be used as an argument in favor of molecular vibrations of magnetic particles.

4. Experiments on demagnetization confirm what has long been known in regard to the effect of vibrations and shocks upon the magnetic condition of iron and steel. They do not invalidate our results upon the heat produced by reversals of magnetization; for a very slight change in position of the molecules might affect the magnetism of a bar, and yet be insufficient to produce the great heating observed in the armatures of dynamo-electric machines.